APPARATUS AND METHODS FOR NOISE-FEEDBACK CONTROLLED OPTICAL SYSTEMS

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FIELD OF THE INVENTION

The present disclosure relates to apparatus and methods for controlling optical systems, and more specifically, to noise-feedback controlled optical systems.

BACKGROUND OF THE INVENTION

Aerospace fiber optic applications present a difficult design challenge relative to other fiber optic applications due to the large number of bulkhead disconnects that may be required, and the relatively high attenuation that occurs at each of these bulkhead connectors. The high attenuation may be the result of the unique environment that the connectors operate in, especially with respect to vibration and electrical signal contamination. As a result, high-speed fiber optic networks using convention connection apparatus and methods may not be possible in some aerospace applications.

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One conventional design technique that can improve the attenuation problem is to use an Avalanche Photodiode (APD) at connections of the optical system instead of a more conventional photodetector. The APD may provide internal gain that can result in several dB of signal-to-noise (S/N) improvement. This may be enough S/N improvement to make possible the use of several additional connectors. The additional S/N may also make possible the use of other lossy components, such as optical switches.

A difficulty of using the APD may arise, however, because the APD's characteristics exhibit variation with temperature. With limited temperature variation (*e.g.* within an office building), the temperature effects can be compensated by measuring the temperature and adjusting the high-voltage bias (and therefore the gain) on the APD to compensate. In some aerospace environments, however, the temperature of the APD can range from -40°C to +100°C. Temperature compensation over such a wide range is generally quite difficult to achieve. Furthermore, there is a potential problem in such applications because the APD may be operated within a few volts of a breakdown voltage, and that breakdown voltage typically changes with temperature (part of the APD characteristics that change with temperature). APD breakdown, while not catastrophic, typically renders the device useless for communications until it is brought back (by reducing the bias voltage) into normal operation. Thus, a link relying on an APD for receiver detection will drop out when such breakdown occurs. Therefore, there is an unmet need for fiber optic systems that provide improved S/N performance in relatively demanding environments, particularly environments characterized by extreme temperatures, vibration and electrical signal contamination of the type which may exist in some aerospace environments.

SUMMARY OF THE INVENTION

The present invention is directed to apparatus and methods for noise-feedback controlled optical systems. Apparatus and methods in accordance with the present invention may advantageously provide improved signal output and improved optical system reliability.

In one embodiment, an apparatus includes a receiver adapted to receive an optical signal and to convert the optical signal to a corresponding electrical signal, and a control circuit coupled to the receiver. The control circuit includes a monitoring component adapted

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to monitor a noise level of at least a portion of the electrical signal and to adjust a gain of the receiver based on the noise level.

In an alternate embodiment, an optical system includes a transmitter adapted to transmit an optical signal, a receiver adapted to receive the optical signal and to output an electrical signal, and a monitoring component. The monitoring component is adapted to monitor a noise level of at least a portion of the electrical signal and to adjust at least one of an amplification of the transmitter and a gain of the receiver based on the noise level.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred and alternative embodiments of the present invention are described in detail below with reference to the following drawings.

FIGURE 1 is a schematic view of a fiber optic system including a control circuit in accordance with an embodiment of the present invention;

FIGURE 2 is a graph of a first output waveform of a photodiode of the fiber optic system of FIGURE 1 at a first gain value;

FIGURE 3 is a graph of a second output waveform of the photodiode of the fiber optic system of FIGURE 1 at a second gain value;

FIGURE 4 is a graph of a third output waveform of the photodiode of the fiber optic system of FIGURE 1 at a third gain value;

FIGURE 5 is a block diagram of a receiver having a control circuit in accordance with an alternate embodiment of the present invention;

FIGURE 6 is a schematic view of an embodiment of the noise energy calculation component of the control circuit of FIGURE 5;

FIGURE 7 is a schematic view of a fiber optic system in accordance with yet another embodiment of the present invention; and

FIGURE 8 is a side elevational view of an aircraft having one or more fiber optic systems or system components in accordance with a further embodiment of the present invention.

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DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to apparatus and methods for noise-feedback controlled optical systems. Many specific details of certain embodiments of the invention are set forth in the following description and in FIGURES 1-8 to provide a thorough understanding of such embodiments. One skilled in the art, however, will understand that the present invention may have additional embodiments, or that the present invention may be practiced without several of the details described in the following description.

Generally, embodiments of apparatus and methods in accordance with the present invention provide noise-feedback controlled optical systems, including improved apparatus and methods for achieving photodiode gain control and optical amplifier amplification control. Such embodiments of the present invention do not require the measurement of temperature, and may provide for an increase in dynamic range, and a decrease in APD gain and/or optical amplifier amplification when the optical signal is high, as described more fully below.

FIGURE 1 is a schematic view of an optical system 100 in accordance with an embodiment of the present invention. In this embodiment, the optical system 100 includes a transmitter 110, and a receiver 120 that includes a photodiode 122. In a particular embodiment, the photodiode 122 is an avalanche photodiode (APD) 122. The transmitter 110 includes a light source 112 (*e.g.* a laser) that transmits an optical signal 114 via a fiber optic link 116 to the receiver 120.

As further shown in FIGURE 1, the photodiode 122 is coupled to a control circuit 130. The photodiode 122 receives the optical signal 114 from transmitter 110 and converts the optical signal 114 into an electrical signal 123 (not shown), and transmits the electrical signal 123 to the control circuit 130. The control circuit 130 may include an amplifier 132 coupled in parallel with a resistor (or load) 134. A feedback loop 136 is coupled between an output of the amplifier 132 and an input voltage (HV) 138 of the photodiode 122. The input voltage (HV) 138 determines a gain of the photodiode 122. The feedback loop 136 includes a monitoring component 140 that is operable to monitor an output of the photodiode 122, and to adjust the input voltage 138 (*i.e.* the gain) of the photodiode 122 based on the monitored output. Preferably, the monitoring component 140 is operable to monitor a noise level in the

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electrical signal 123 from the photodiode 122, and to adjust (increase and decrease) the input voltage 138 to maintain a desired noise level (*e.g.* a desired RMS value) output by the photodiode 122. It will be appreciated that the monitoring component 140 may monitor one or more portions of the electrical signal 123 from the photodiode 122, or may monitor the entire electrical signal 123.

For example, in one embodiment, the general response of an APD photodiode 122 to light may be expressed as the following Equation (1):

$$I_T^{\,2} = \underbrace{M^2 I_S^2}_{signal} + \underbrace{2qF(M)M^2 i_S B}_{signal\ shot\ noise} + \underbrace{2qF(M)M^2 I_{db} B}_{multiplied\ dark\ noise} + \underbrace{\frac{4kTB}{R}}_{resistor\ noise} + \underbrace{2qI_{ds}B}_{unmultiplied\ dark\ noise} \qquad (1)$$

where I_T is the total current output of the APD 122, including noise, M is the APD internal gain, I_S is the unmultiplied signal current, q is electronic charge, $F(M)$ is the APD's excess noise factor, I_{db} and I_{ds} are the multiplied and unmultiplied dark current densities, respectively, k is Boltzmann's constant, T is absolute temperature, R is the receiver transimpedance, and B is the inverse of the data rate. Equation (1) is a known relation (*e.g.* see *Optical Communications* by M.J.N. Sibley, published by McGraw Hill, Equation 4.32).

The first term in Equation (1) is the electrical signal 123. The other four terms in Equation (1) are a signal shot noise, a multiplied dark noise, an amplifier noise, and an unmultipled dark noise. All four terms contribute to the noise of the output electrical signal 123 of the APD photodiode 122. All of the terms except the first term (the desired signal) and the second term (the signal shot noise) exist always. The first two terms exist only in the presence of light (that is, a data '1'). For low values of M the noise statistics are dominated by the last two terms of Equation (1). As M is increased and assuming that the signal current is much greater than the APD's multiplied dark current ($I_s >> I_{db}$), the noise variance during intervals of data '1's becomes significantly greater than the variance during data '0's.

Example output electrical signals of the photodiode 122 are shown in FIGURES 2-4. Specifically, FIGURE 2 is a graph 200 of a first output waveform 202 of the APD photodiode 122 of the optical system 100 of FIGURE 1 at a first gain value 204. Similarly, FIGURES 3 and 4 show second and third output waveforms 222, 242 of the APD photodiode

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122 at second and third gain values 224, 244, respectively. FIGURES 2-4 illustrate the emergence of noise in the bits corresponding to the presence of light as the APD photodiode 122 is increased. FIGURES 2-4 were created using an optical communications simulation tool called LinkSim commercially available from RSoft Design Group of Ossining, New York. In these simulations, a Vertical Cavity Surface Emitting Laser was used as a source which was launched into a multimode fiber and received by an APD connected to a transimpedance amplifier with 500 Ω feedback.

As shown in FIGURE 2, at a relatively low gain 204 (M=1), the noise of the electrical signal 123 is dominated by the terms that are independent of the gain M 204 in Equation (1), so that the noise levels for the two signal states (*i.e.* light present 206 and light absent 208) are virtually identical. In FIGURE 3, at the intermediate gain 224 (M=11), the multiplied noise of the second term in Equation (1) begins to emerge for high-state bits (*i.e.* light present 226). And in FIGURE 4, at the relatively large gain 244 (M=21), the ratio of high-state (*i.e.* light present 246 or data '1') noise to low-state (*i.e.* light absent 248 or data '0') noise is quite large. FIGURES 2-4 demonstrate that a ratio of the noise (variance) in the two binary states of the data may provide a suitable discriminator for determining when the APD photodiode 122 is approaching a breakdown.

In one particular embodiment, by measuring instantaneous analog output from the photodiode 122 (or from the receiver 120), subtracting the mean (signal) from each such measurement, squaring the output, and integrating these measurements over a one-bit interval, a one-bit interval estimate of a noise energy for the particular state (high or low) may be obtained. Thus, estimates of noise energy for like states may be determined, and the ratio of these two energy estimates may be compared. When the ratio exceeds an established threshold, the monitoring component 140 of the control loop 130 of FIGURE 1 may decrease the input gain 138 of the photodiode 122 so that the photodiode 122 stops increasing the gain of the signal 114 from the transmitter 110. When the photodiode 122 (or receiver 120) output again calls for *lower* voltage bias HV (*i.e.* increased gain) rather than *higher* voltage bias, the control loop 130 may increase the input gain 138 accordingly.

FIGURE 5 is a block diagram 300 of a receiver 320 having a control circuit 330 coupled to an APD photodiode 322 in accordance with an embodiment of the present

invention. In this embodiment, the control circuit 330 includes an amplifier 332 coupled in parallel with a resistor 334 to the APD photodiode 322, and a monitoring loop 140 coupled between an output of the amplifier 322 and the input gain 338 of the APD photodiode 322. A condition determining component 342 receives an electrical signal 323 (not shown) from the APD photodiode 322 (via the amplifier 332) and determines whether the input signal indicates the presence or absence of light (*i.e.* whether input is '1' or '0').

A state means calculation component 344 may then compute the high- and low-state means (A and –A) of the electrical signal, and a noise energy calculation component 346 may compute a noise energy over the current bit interval. A high energy calculation component 348 may then compute an average energy for the high-state A, and a low energy calculation component 350 may compute an average energy for the low-state –A. A ratio component 352 may then calculate a ratio of the average energies for the high- and low-states A, -A, and transmit the calculated ratio to a comparator 354 which may compare the calculated ratio with a predetermined threshold 356. Based on the results of this comparison, the comparator 354 may adjust (increase or decrease) the input voltage 338 of the APD 322, or do nothing until a prescribed condition is satisfied. As described above, in a particular embodiment, when the ratio approaches or exceeds a threshold indicating that a breakdown voltage of the APD 322 is eminent, the comparator 354 may interrupt the input gain 338 to reduce the gain of the APD 322 to prevent breakdown of the APD 322 and possible interruption of the operation of the receiver 320. In a preferred embodiment, the comparator 354 interrupts the input gain 338 to the APD 322 when the calculated ratio equals or exceeds the predetermined threshold 356.

FIGURE 6 is a schematic view of an embodiment of the noise energy calculation component 346 of the control circuit 330 of FIGURE 5. As shown in FIGURE 6, the noise energy calculation component 346 includes a subtractor component 360 that receives the high- and low-state means from the state means calculation component 344. In one particular embodiment, +A is subtracted by the subtractor component 360 if other parts of the circuit determine that a logic '1' was sent, otherwise –A is subtracted. Next, a squaring function 362 squares the output from the subtractor component 360. In a particular embodiment, the squaring function 362 may be implemented using a device like the Model

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AD8362 TRUPWR® Detector commercially available from Analog Devices of Norwood, Massachusetts. Finally, an integrate-and-dump circuit 364 receives the output from the squaring function 362 and integrates the output over the bit interval of bit *n*. In a particular embodiment, the integrate-and-dump circuit 364 can be implemented using the methods disclosed in U.S. Patent No. 6,128,112 issued to Harres. In another embodiment, the methods disclosed in U.S. Patent No. 6,128,112 can also be used to perform the high-speed '1' or '0' decision of the condition determining component 342 of FIGURE 5.

Embodiments of methods and apparatus in accordance with the present invention may provide significant advantages over the prior art. In one aspect, by monitoring the level of noise in the optical signal and controlling the receiver accordingly, optical systems in accordance with the present invention may provide significantly improved performance over alternate systems. For example, using a noise-feedback controlled control circuit as described above, an APD may be more effectively utilized in a wider range of environments, including those which exhibit significant variations in temperature such as some aerospace environments. Because the noise in the output of the APD may be monitored and utilized to adjust the input gain of the APD, the performance of the APD may be more effectively utilized by operating the APD near its limit of performance while substantially reducing or eliminating avalanche breakdown and corresponding signal interruption. Thus, optical systems in accordance with the present invention may provide improved output, as well as improved reliability.

Additional advantages may also be realized throughout the optical system in accordance with the present invention. For example, by enabling the robust usage of APD's at a plurality of connections (*e.g.* at bulkheads) throughout the entire optical system, significant improvement in an aircraft link budget may be realized. In one representative example, an improvement of 10dB or more may be realized in an aircraft link budget. Link margin deficiency is currently one of the primary impediments to implementing high-speed optical networks on aircraft. Thus, embodiments of the present invention may significantly improve the link budgets on aircraft, thereby enabling increased usage of optical systems on aircraft and in other applications as well. Also, because the APD provides internal gain that may result in several dB of signal-to-noise (S/N) improvement, the improvement in the link

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budget may make possible the use of several additional connectors. The additional S/N provided by embodiments of the present invention may also make possible the use of other lossy components, such as optical switches.

Finally, embodiments of apparatus and methods in accordance with the present invention provide improved methods of achieving photodiode gain control. For example, there is no need to measure or monitor the temperature of the surrounding environment, and embodiments of the present invention provide increased dynamic range of the photodiode. In one particular aspect, by decreasing APD gain when the optical signal is high, the embodiments of apparatus and methods in accordance with the present invention perform a function which conventional temperature compensation circuits cannot achieve.

It may be appreciated that the teachings of the present invention may be applied to other components of the optical system, and that the invention is not limited to the exemplary embodiments described above. For example, FIGURE 7 is a schematic view of an optical system 400 in accordance with yet another embodiment of the present invention. In this embodiment, the optical system 400 includes an optical amplifier 402 positioned ahead of a detector 404. An electronic amplifier 410 is coupled downstream of the detector 404. The optical system 400 further includes a control circuit 430 that includes a monitoring component 440. The control circuit 430 provides a first feedback loop 432 to controllably adjust the input gain (HV) 442 to the detector 404, or a second feedback loop 434 to control the amplification of the optical amplifier 402, or both.

In operation, the optical amplifier 402 receives an input signal 406, and transmits an amplified signal 408 to the detector 404. The optical amplifier 402 boosts the input signal 406 so that it produces a relatively large current in the detector 404 upon conversion from light to electrical energy. In this way, the resulting electrical signal can be made much larger than the noise currents occurring mainly in the electronic amplifier 410. Thus, the optical amplifier 402 serves a purpose that is similar to the Avalanche Photodiode (APD) described above. In the case of the APD, however, the additional amplification occurs *after* the conversion from optical to electrical energy but, like the optical amplifier 402, precedes the noise of the electronic amplifier 410 and thus allows an improvement in the Signal-to-Noise Ratio (SNR) which results in better communications reliability (*e.g.* the Bit Error Rate is

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improved). Conversely, in the case of the optical amplifier 402 shown in FIGURE 7, the additional amplification occurs prior to the conversion from optical to electrical energy.

Typically, the optical amplifier 402, like the APD, may exhibit noise with amplitude that is signal dependent. In the case of the optical amplifier 402, this signal-dependent component may occur as the result of interaction between signal photons and spontaneous emission photons, as described more fully, for example, in *Lightwave Systems With Optical Amplifiers*, by N.A. Olsson, published in the Journal of Lightwave Technology, Vol. 7, No. 7, July, 1989. As with the APD, there may be an excess noise factor that may cause such noise to increase with gain at a somewhat higher rate than the signal itself, thereby degrading the SNR at highest gain levels. Therefore, in alternate embodiments of the present invention, noise-feedback control circuit 430 of the type described above with reference to FIGURES 1, 5, and 6 may be operatively coupled to the various components of the optical system 400 to monitor the noise level of an output signal (*e.g.* from the detector 404 or from the electronic amplifier 410) and to adjust the amplification of the optical amplifier 402 or the gain of the detector 404 (or both).

It will be appreciated that a wide variety of apparatus may be conceived that incorporate optical systems having noise-feedback control in accordance with various embodiments of the present invention. For example, FIGURE 8 is a side elevational view of an aircraft 600 having one or more optical systems 602 in accordance with the present invention. In general, except for the optical systems 602, the various components and subsystems of the aircraft 600 may be of known construction and, for the sake of brevity, will not be described in detail herein. As shown in FIGURE 8, the aircraft 600 includes one or more propulsion units 604 coupled to a fuselage 605, wing assemblies 606 (or other lifting surfaces), a tail assembly 608, a landing assembly 610, a control system 612 (not visible), and a host of other systems and subsystems that enable proper operation of the aircraft 600. The aircraft 600 shown in FIGURE 8 is generally representative of a commercial passenger aircraft, including, for example, the 737, 747, 757, 767, and 777 models commercially-available from The Boeing Company. The inventive apparatus and methods disclosed herein, however, may also be employed in any other types of aircraft, such as rotary aircraft or manned military aircraft, including those described, for example, in The Illustrated

Encyclopedia of Military Aircraft by Enzo Angelucci, published by Book Sales Publishers, September 2001.

It may also be appreciated that embodiments of the present invention may be incorporated in other types of aerospace vehicles, including, for example, a planetary probe, a satellite or other types of spacecraft. In further embodiments, embodiments of the present invention may be incorporated into a wide variety of vehicles, including land, sea, and undersea vehicles, such as automobiles, trains, ships, submarines, submersibles, or any other suitable vehicle type.

With continued reference to FIGURE 8, the aircraft 600 may include one or more embodiments of optical systems 602a that operate at connections across bulkheads within the airframe and/or fuselage of the aircraft structure. Similarly, the aircraft 600 may include one or more noise-feedback controlled optical systems 602b incorporated into the flight control system 612, and one or more noise-feedback controlled optical systems 602c for controlling the propulsion units 604, including, for example and not by way of limitation, those optical systems described in U.S. Patent No. 5,809,220 issued to Morrison *et al.*, U.S. Patent No. 6,369,897 B1 issued to Rice *et al.*, U.S. Patent No. 6,266,169 B1 issued to Tomooka *et al.*, U.S. Patent No. 5,653,174 issued to Halus, U.S. Patent No. 5,295,212 issued to Morton *et al.*, U.S. Patent No. 5,222,166 issued to Weltha, and U.S. Patent No. 5,119,679 issued to Frisch. Clearly, a wide variety of optical systems 602 in accordance with the present invention may be conceived for incorporation into the various subsystems of the aircraft 600.

While the preferred embodiment of the invention has been illustrated and described, as noted above, many changes can be made without departing from the spirit and scope of the invention. Accordingly, the scope of the invention is not limited by the disclosure of the preferred embodiment. Instead, the invention should be determined entirely by reference to the claims that follow.

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